

HUNTSVILLE RESEARCH & ENGINEERING CENTER

Contract NAS8-20082

Date 13 Sept. 1968

Doc. TN 54/20-30, LMSC/HREC A791774

Title: PRELIMINARY DATA FOR PLUME DEFINITION OF THE R4D ENGINE FOR THE COMMAND SERVICE MODULE REACTION CONTROL SYSTEM

FOREWORD

This document presents preliminary exhaust plume characteristics for the R4D engine that is used by the Reaction Control System of the Command Service Module. This study was performed by Lockheed's Huntsville Research & Engineering Center while under subcontract to Northrop Nortronics (NSL PO 5-09287) for the Aero-Astroynamics Laboratory of Marshall Space Flight Center (MSFC), Contract NAS8-20082. This task was conducted under Appendix B-1, Schedule Order B-100, Paragraph A, in response to a request by Mr. Keith Henson, R-AERO-AD.

DISCUSSION

The Reaction Control System (RCS) of the Command Service Module (CSM) uses the Marquardt R4D engine to make attitude changes. The operating characteristics of this engine, as used in this study, are given in Table 1. The plume flow field for the R4D was generated using Lockheed/Huntsville's Method of Characteristics (MOC) Computer Program, Reference 1. The MOC program utilizes data generated by the NASA/Lewis Thermochemical Program, Reference 2, to account for real gas effects.

Because the prediction of a real gas, three-dimensional, plume flow field is a highly complex problem, certain assumptions were made to simplify the analysis. These assumptions are:

- The flow was assumed to be inviscid and axially symmetric.
- The gas dynamic effects of particles of finite size existing in the flow field were neglected. These particles can consist of solid and/or liquid material. Currently, Lockheed is not equipped to handle multi-phase flow problems.

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- Chemical freezing was assumed to occur just prior to the thermochemical state where the equilibrium and frozen isentropic exponents (γ) began to deviate significantly. This technique was used because it is known that the flow chemically freezes at some downstream locations in the flow field. Furthermore, a more accurate determination of the freezing conditions requires the use of complex finite-rate chemistry techniques that are beyond the present effort. Using the deviation in γ technique, regions of the plume where the Mach number was less than or equal to 7.0, the flow was considered to be in chemical equilibrium, and for regions of the plume where the Mach number was greater than or equal to 7.0, the flow was considered to be chemically frozen. This assumption will probably give results which differ from those coming from the finite rate thermochemical program — the largest deviation being in the chemical composition.
- For Mach numbers greater than or equal to 7.0, the flow was treated as an ideal gas which has the properties of the chemically frozen flow. The constituents considered to exist in the flow field for the chemically frozen condition are listed together with the applicable mole fractions in Table 2.
- Zero back-pressure or vacuum-expansion option of the MOC program was utilized to simulate the ambient operating conditions of the R4D engine. In actuality, because of numerical problems within the program the flow is expanded to an angle which is just slightly less than the full vacuum expansion angle.

Non-gaseous forms of the constituents listed in Table 2 were not considered in the thermochemical analysis. The ability of the NASA/Lewis Thermochemical Program to handle non-gaseous species is restricted by the lack of thermochemical data for the liquid and solid products. Since the possibility of non-gaseous species occurring in the plume exists, vapor pressure data for the listed species were correlated with flowfield data to determine if these forms could occur in the continuum region of the plume. Conditions which could lead to the formation of non-gaseous H_2O were noted to exist for flows of Mach 13.0 and higher. Conditions favorable to the phase change of CO_2 exist for flows of Mach 19.0 and higher. Phase change will not occur for CH_4 , H_2 , N_2 and CO in the region of interest.

Because of the high velocities in the plume flow field, non-gaseous species may or may not be formed in the plume region shown. Determination of the actual onset point of phase change and calculation of a multi-phase plume flow field cannot be made unless the computer programs now available are modified.

Flowfield calculations were initiated using a start line based on a one-dimensional solution for the nozzle with the flow angle distributed along the nozzle exit radius. This method was used because the R4D engine nozzle contour data were not available at the beginning of the study. The plume flow field for the R4D engine is described by the streamline distribution shown in Figure 1. The axial, X, and radial, R, distances are measured from the coordinate system origin which is located on the plume centerline in the plane of the nozzle exit. Transition from continuum to free-molecular flow is assumed to occur across a "continuum/free-molecular boundary" which was computed as outlined in Reference 3. The "continuum/free-molecular boundary" is represented by dotted lines in Figures 1 and 2. No transition region was considered in the plume calculation. This results in a discontinuity in the flow parameters across this line.

Figure 1 also shows the distribution of mass flow within the plume flow field. Mass flow information is shown as a percentage of the total mass flow in the plume and represents the mass flow through the region below the associated streamline.

Figure 2 shows lines of constant Mach number for the continuum and free-molecular regions. Mach number is constant along a streamline in the free-molecular region. Although the limiting inviscid expansion line is shown in Figure 1 (100 % mass flow streamline) program calculations were not made beyond the $M = 10.862$ streamline shown in Figure 2 which corresponds to the limiting flow conditions defined by the flowfield Knudsen number criteria for free molecular flow.

For chemically frozen flow, in the absence of shock waves, the flow properties in the continuum region of the plume are functions of Mach number only. Plots of pressure, temperature, density and velocity versus Mach number are presented in Figures 3 through 6. Thus, using the continuum Mach number distribution in the plume, Figure 2, together with the flow property distributions given in Figures 3 through 6, the properties of the flow at a specified region of the continuum plume can be determined.

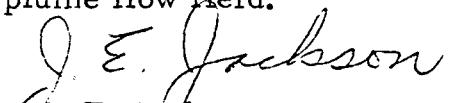
Flowfield properties in the free-molecular region do not exhibit the same relationships as those in the continuum region. In the free molecular region temperature, velocity and Mach number are constant along the streamlines. The density of the flow field is allowed to vary inversely as the cross-sectional area of the stream tubes that are formed by the adjacent streamlines (Reference 3). In the free-molecular region gamma has a constant value equal to 1.667.

The viscous option of the MOC program was used to determine the amount of mass contained in the boundary layer at the nozzle exit. The program utilizes a simplified boundary layer theory to determine boundary layer and displacement thickness for the viscous flow case. Results from these calculations show that less than 6% of the total mass is contained in the boundary layer. A more detailed discussion of the boundary layer study will be presented in a later report.

The description of the plume flow field for the R4D engine, as presented in this report, was limited to the general region where impingement is most likely to occur on the OWS-LM. This was done by limiting the axial range of the numerical calculations in the plume flow field.



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Attach: (1) References
(2) Tables 1 through 3
(3) Figures 1 through 6

REFERENCES

1. Prozan, R. J., "Development of a Method-of-Characteristics Solution for Supersonic Flow of an Ideal, Frozen or Equilibrium Reacting Gas Mixture," LMSC/HREC A782535, Lockheed Missiles & Space Company, Huntsville, Ala., April 1966.
2. Zeleznik, F. J. and S. Gordon, "A General IBM 704 or 7094 Computer Program for Computation of Chemical Equilibrium Compositions, Rocket Performance and Chapman-Jouguet Detonations," NASA TN D-1454, October 1962.
3. Robertson, S. J., "A Method for Calculating Flow Field Properties in Low Density Plumes," LMSC/HREC A784697, Lockheed Missiles & Space Company, Huntsville, Ala., October 1967.

Table 1
OPERATING CHARACTERISTICS OF R4D ENGINE

		Engine Parameters
Oxidizer	N_2O_4	$A/A^* = 40:1$
		$O/F = 2.03$
		$P_c = 96.5$
Fuel	CH_3NHNH_2	$\theta_{exit} = 8^\circ$
	(Monomethylhydrazine)	$D_{exit} = 5.46$
		$\dot{m}_{TOTAL} = 0.314 \text{ lbm/sec}$
Thrust (nominal) = $100 \pm 5 \text{ lb}_f$ vacuum; Thrust (theoretical) = 105 lb_f		

Table 2
COMPOSITION OF PLUME FLOW FIELD

Constituents	Mole Fraction
$CH_4(G)^*$	0.00048
$CO(G)$	0.00095
$CO_2(G)$	0.16975
$H_2(G)$	0.15975
$H_2O(G)$	0.33950
$N_2(G)$	0.32950
Trace Species	0.00007

* (G) denotes gaseous phase.

Table 3
FREE MOLECULAR PLUME PROPERTIES

Mach Number	Static Temperature ($^\circ R$)	Velocity (ft/sec)
10.862	344.76	12104.0
15.689	169.20	12248.0
16.810	147.82	12266.0
18.565	121.62	12287.0
19.934	105.71	12300.0
20.302	101.96	12303.0

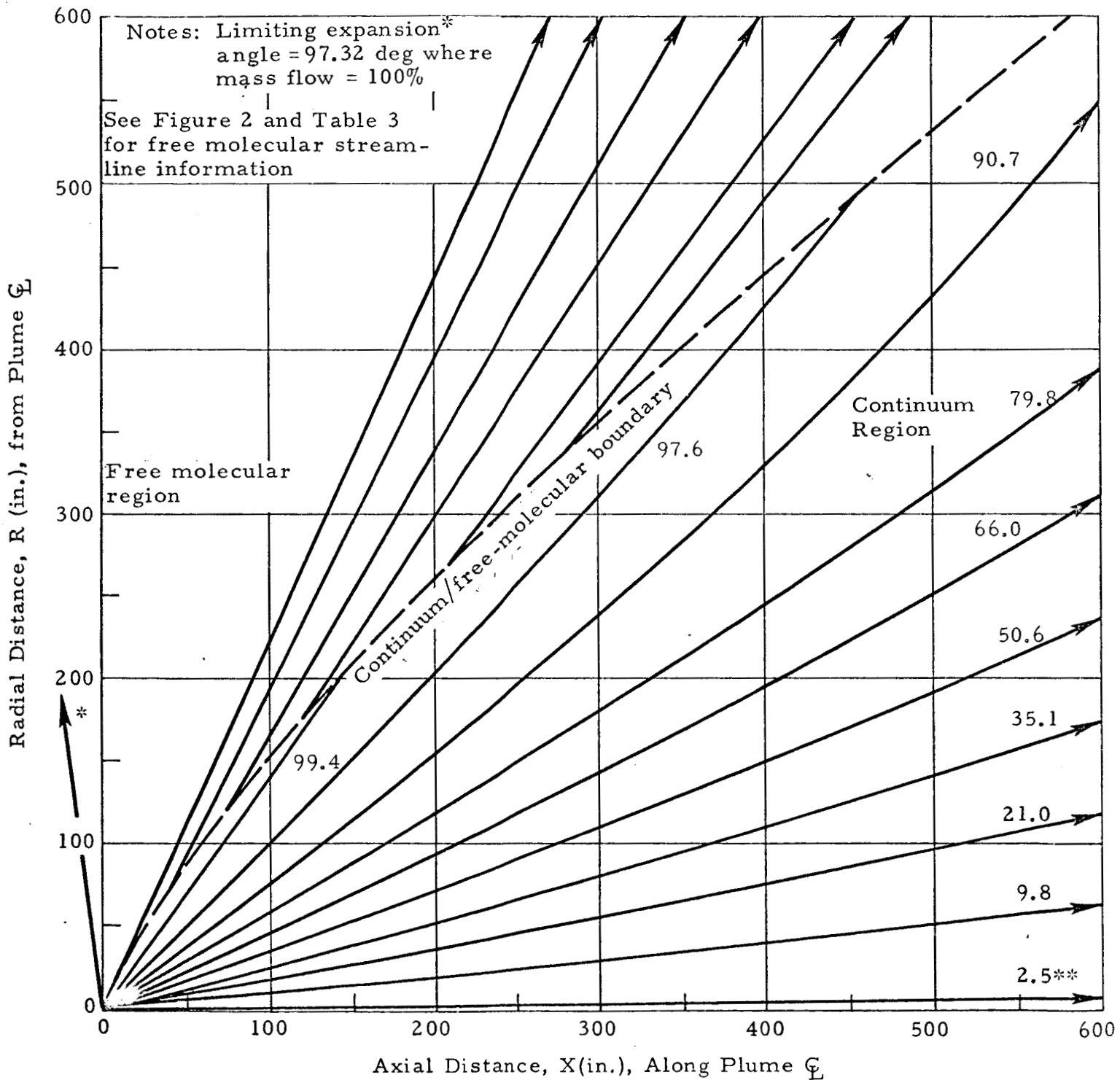


Figure 1 - Location of Streamlines and Mass Flow** Distribution (in Percent of Total) in the R4D Engine Plume Flow Field

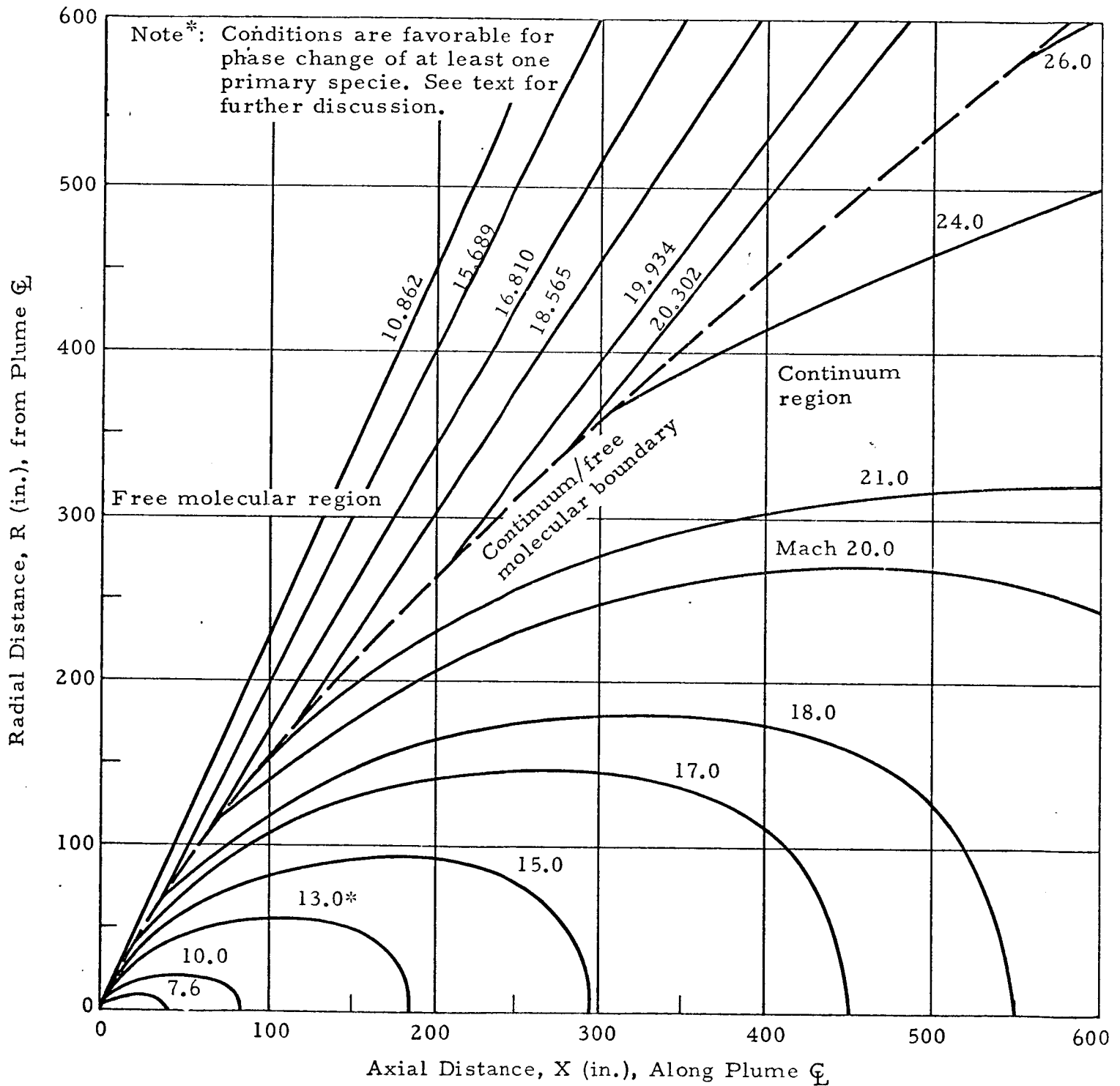


Figure 2 - Lines of Constant Mach Number in the R4D Engine Plume Flow Field

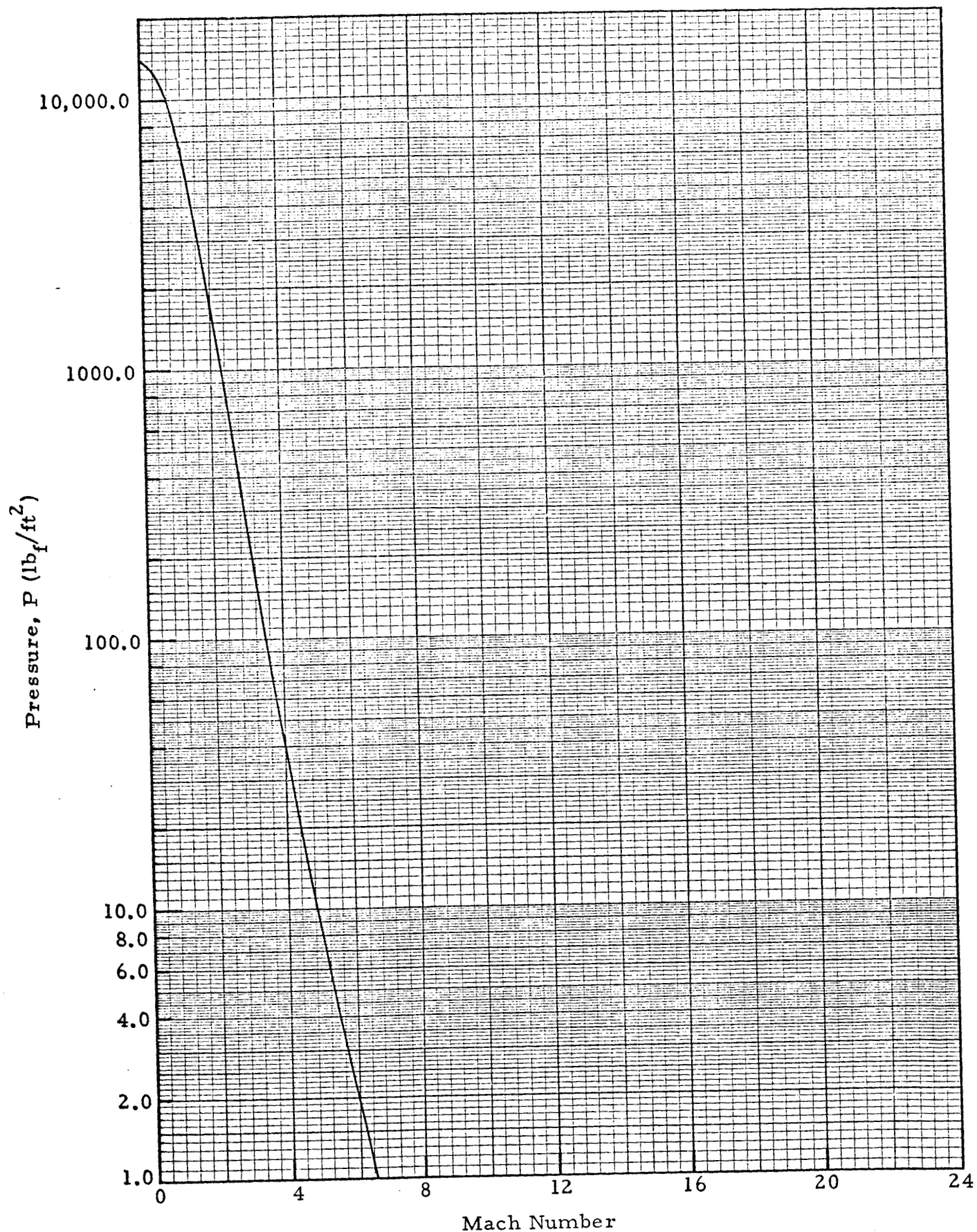


Figure 3a - Static Pressure as a Function of Mach Number in the R4D Engine Plume Continuum Flow Field

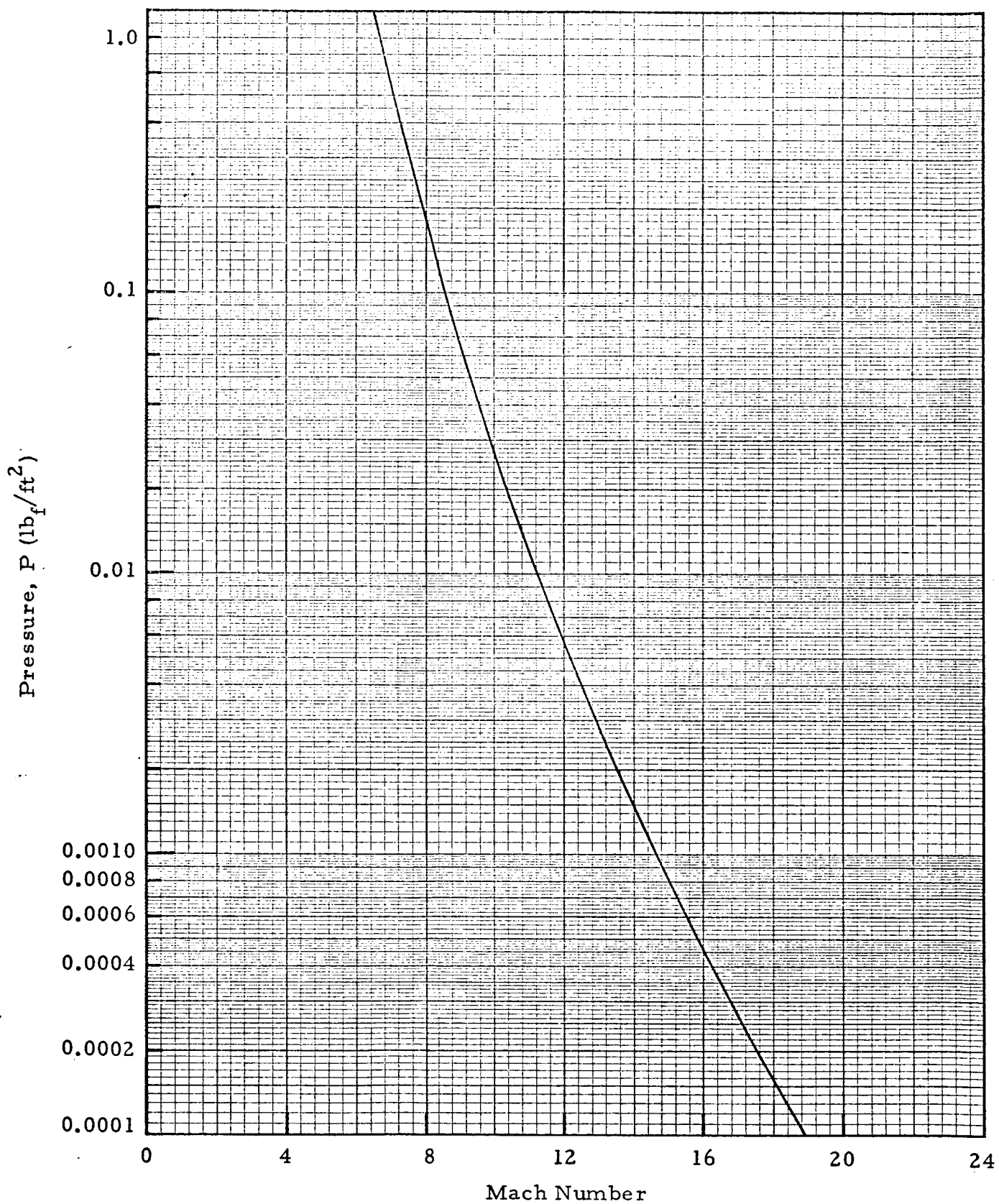


Figure 3b - Static Pressure as a Function of Mach Number in the R4D Engine Plume Continuum Flow Field

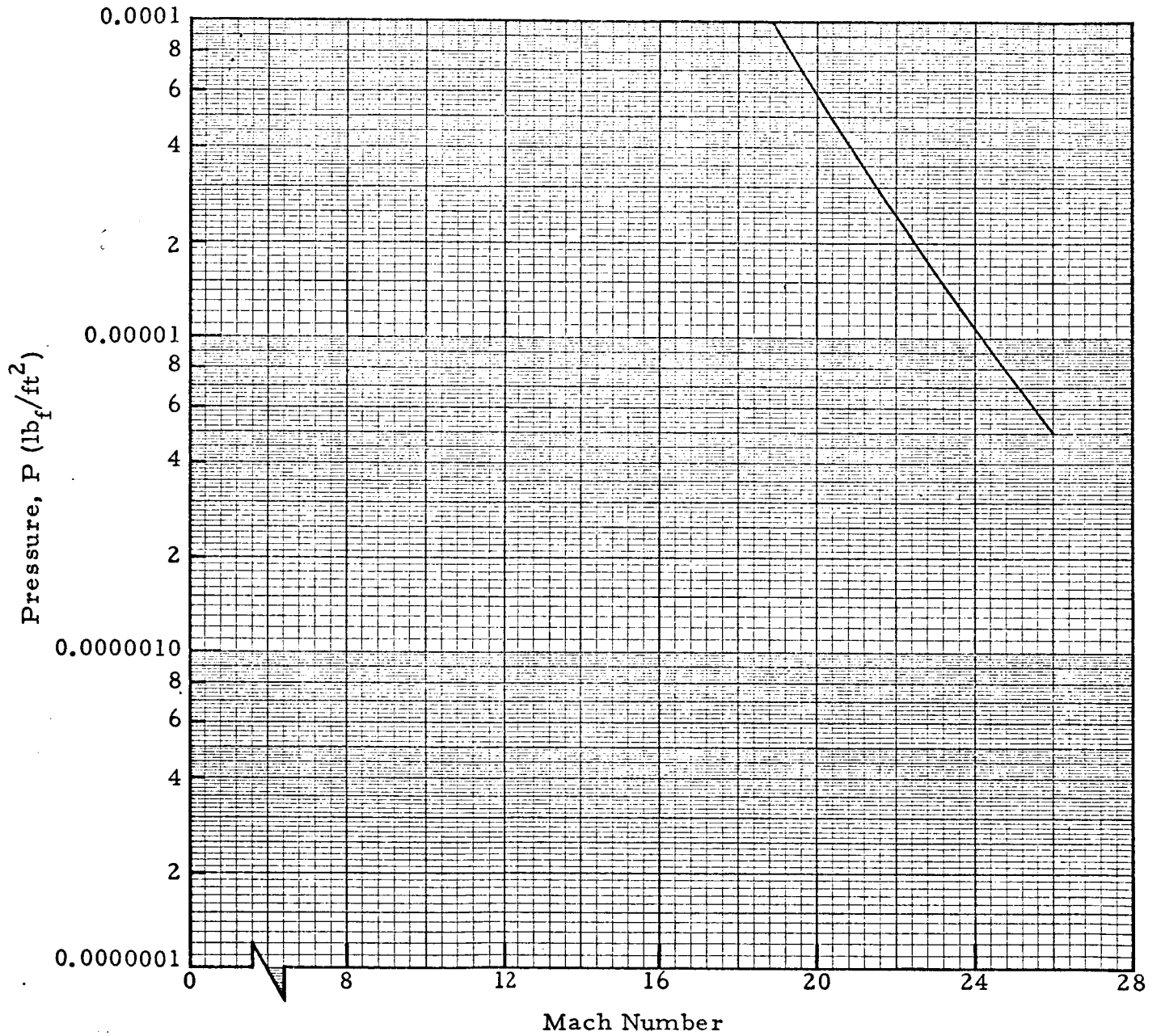


Figure 3c - Static Pressure as a Function of Mach Number in the R4D Engine Plume Continuum Flow Field

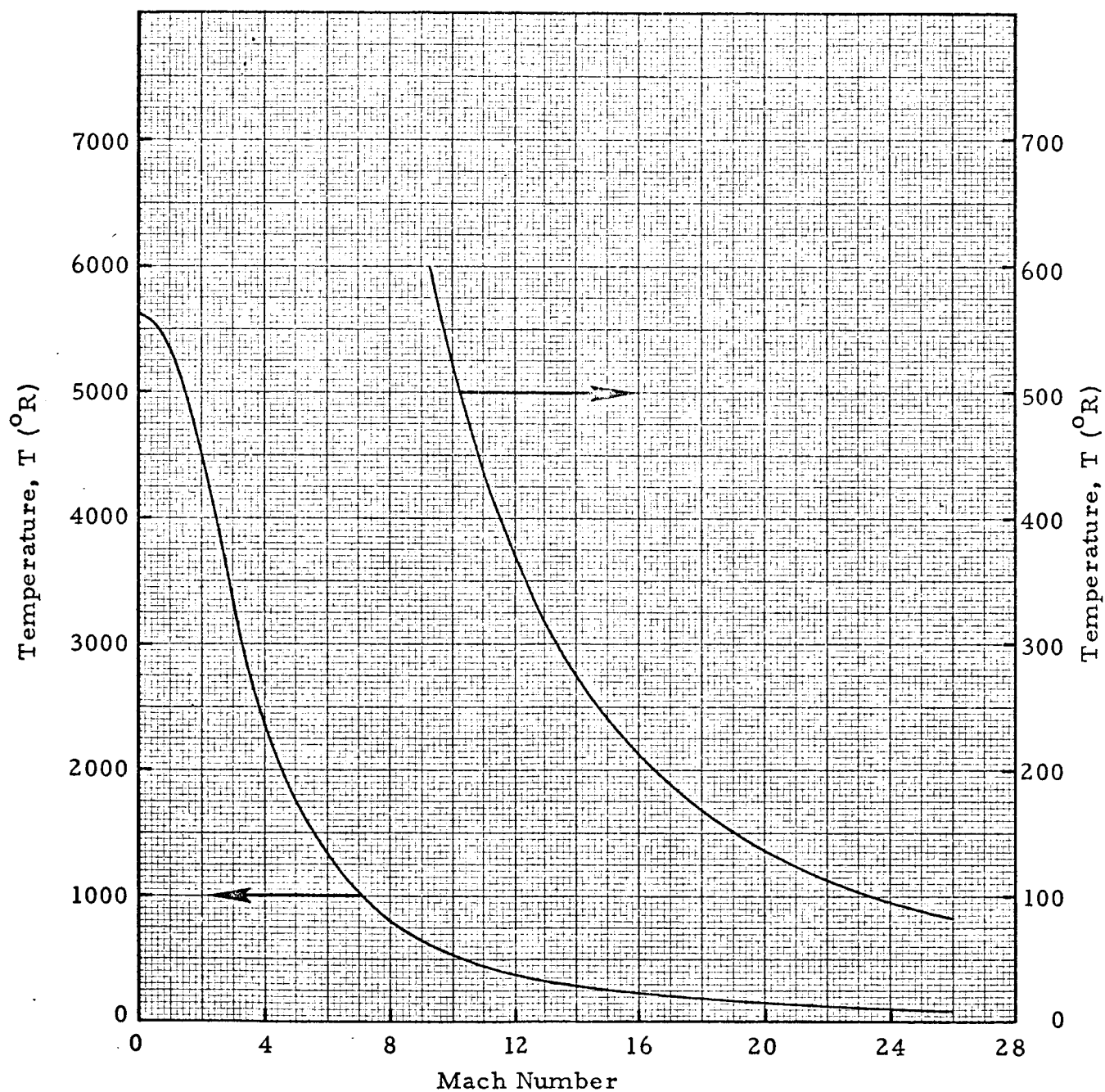


Figure 4 - Static Temperature as a Function of Mach Number in the R4D Engine Plume Continuum Flow Field

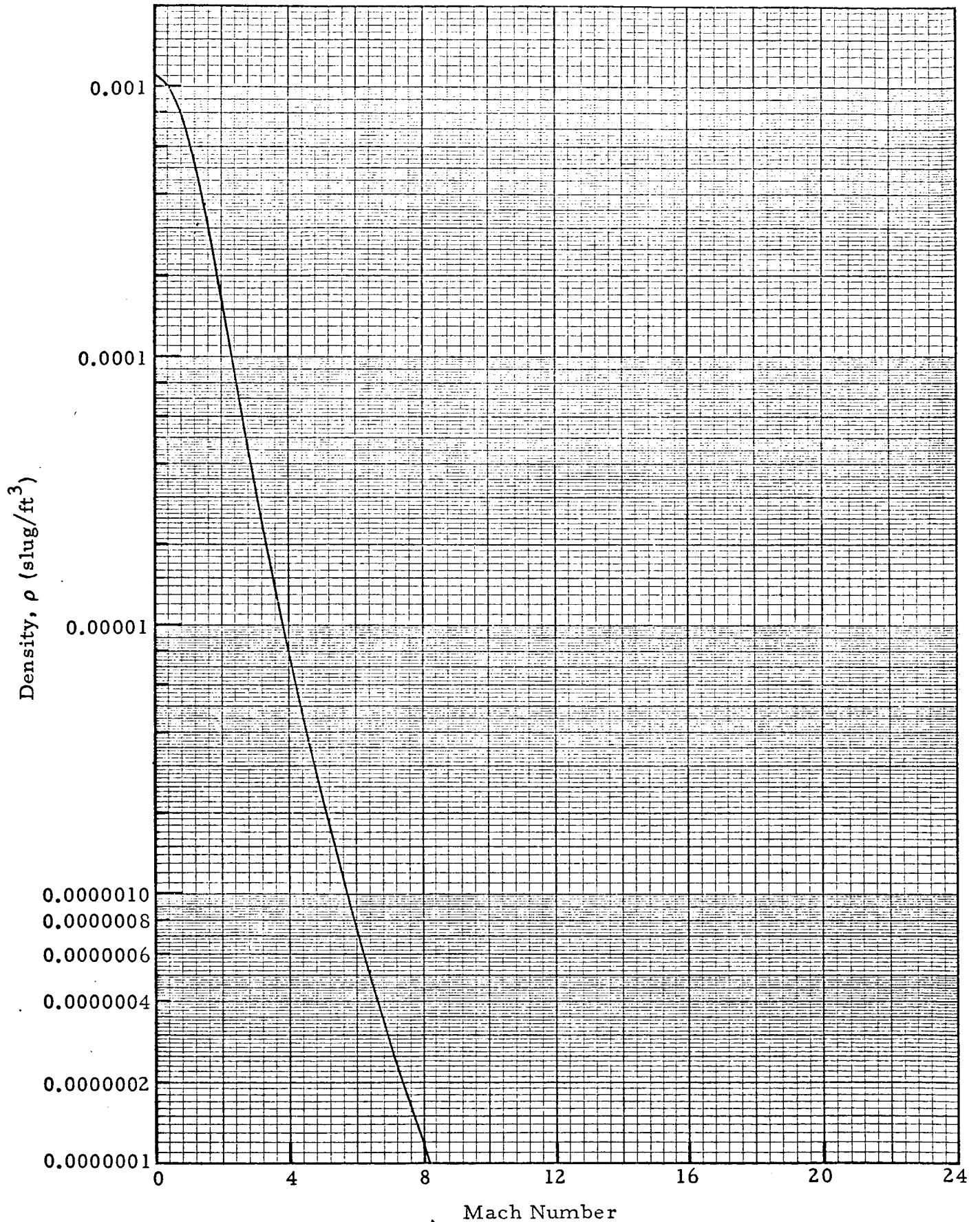


Figure 5a - Density as a Function of Mach Number in the R4D Engine Plume Continuum Flow Field

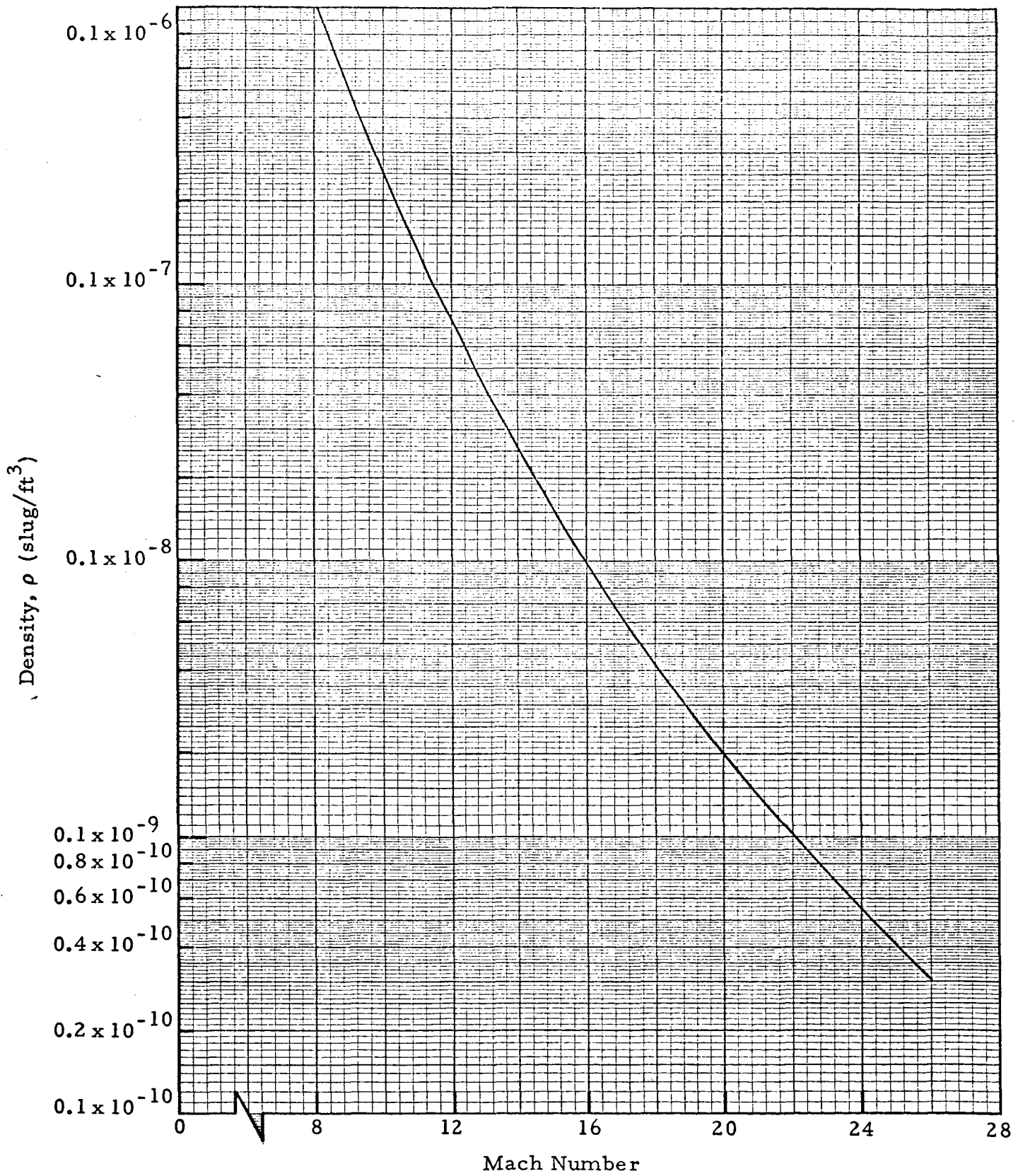


Figure 5b - Density as a Function of Mach Number in the R4D Engine Plume Continuum Flow Field

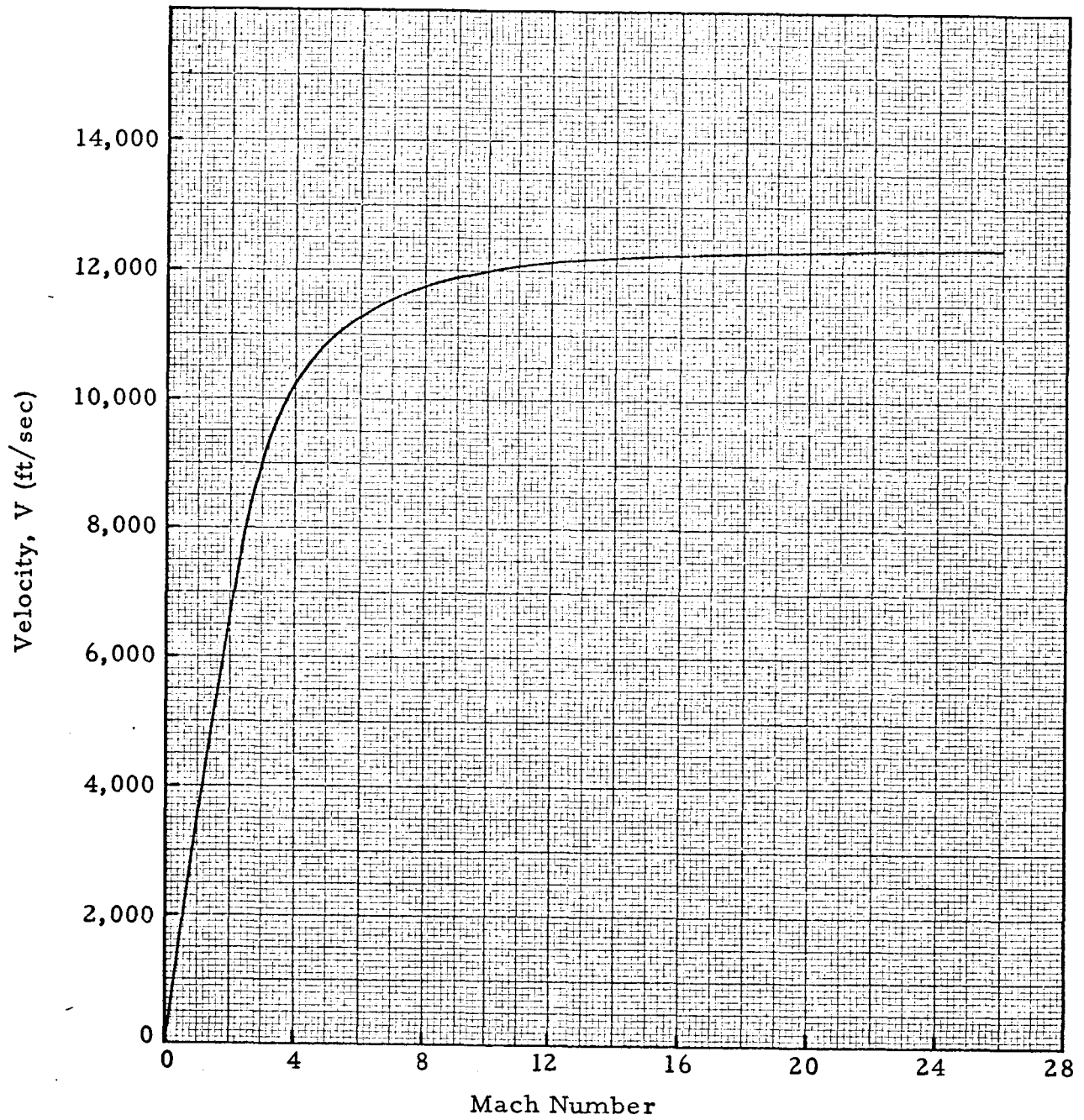


Figure 6 - Velocity as a Function of Mach Number in the R4D Engine Plume Continuum Flow Field